Study on the shear resistance characteristics of clay-stone mixtures under freeze-thaw cycles based on nuclear magnetic resonance

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Abstract. To investigate the shear strength characteristics of clay-stone mixtures in the northwest slope region under freeze-thaw conditions, triaxial and nuclear magnetic resonance experiments were conducted. The study quantitatively explains how freeze-thaw cycles affect shear resistance through changes in pore structure, with results showing a pattern of decreasing, then slightly increasing, and ultimately decreasing shear strength parameters. The findings suggest that changes in pore structure and uniformity contribute to the fluctuations in cohesion and internal friction angle of the mixtures.

Keywords:freeze-thaw cycles; nuclear magnetic resonance; pore structure; fractal dimension; shear strength.

1. Introduction

As one of the widely used building materials in the field of engineering, cohesive soil-rock mixture is a major component of reservoir slopes and soil-rock dams. However, the significant physical property differences between the soil and rock blocks result in noticeable nonlinear mechanical characteristics [1] [2]. In the cold regions of northwest China where there is a large temperature difference between day and night, the surfaces of reservoir slopes and the buried soil-rock mixtures in hydraulic engineering projects are subjected to long-term freeze-thaw cycles, leading to significant changes in the structural distribution and moisture content of soil particles [3] [4]. Consequently, changes in pore water pressure and compressibility characteristics within the soil mass are observed [5]. Zheng Yun et al. [6] identified and classified soil structure elements, establishing a theoretical system for quantitatively analyzing soil structure. With the rapid advancement of the new development pattern in western China, the application effectiveness of rock-soil materials in engineering projects in the cold and arid regions of northwest China has become a highly concerned issue [7], leading to rapid development in the study of the mechanical properties of soil-rock mixtures. Ning Jincheng et al. [8] studied the strength variation of soil-rock mixtures under the combined effects of stone content and confining pressure. In order to reveal the shear strength variation law of cohesive soil-rock mixtures at a microscopic level, researchers conducted non-destructive and rapid nuclear magnetic resonance testing of its microstructure[9]. Considering the heterogeneity, discontinuity, and randomness of the soil-rock mixture, fractal theory is introduced to more clearly quantify the internal morphological changes of the material[10][11]. Liu Xinrong et al. [12] studied the shear characteristics of mixed soil under the influence of multiple factors, obtained the fractal characteristics of shear surfaces and evolution of shear strength.

This paper investigates the reshaping of cemented sand and gravel clay. On the one hand, it detects and analyzes the changes in pore size and structure, while on the other hand, it combines fractal theory to analyze the complexity of the pores and the uniformity of their shapes. Finally, it collectively interprets the variations in the measured mechanical parameters, which have guiding significance for practical engineering in cold regions.

2. Nuclear Magnetic Resonance (NMR) detection

2.1 Experimental sample preparation

Six sets of samples with freezing and thawing cycles of 0, 1, 2, 3, 6, and 10 times are prepared as controls by placing the reshaped samples with a stone content of 40% into a constant temperature freezer at -25°C for 12 hours, followed by natural thawing at an ambient temperature of 20°C for 12 hours after each freezing cycle.

2.2 Analysis of pore distribution

Nuclear magnetic resonance detects H atoms in fluids. T_2 spectrum peak position determines pore radius, and peak area determines pore number. Figure 3 (a-f) shows T_2 spectrum curves after freeze-thaw cycles. Water freezing on sample surface reduces moisture content, decreasing peak spectrum area. Integration of T_2 peak areas (Figure 2) shows main peak signal initially decreases then increases, main peak width increases, and sub-peaks move backward and upward with more cycles(Figure 1). Water freezing expands inside sample, causing frost heave forces and larger pores. Increased pores lead to looser sample and reduced cohesion.

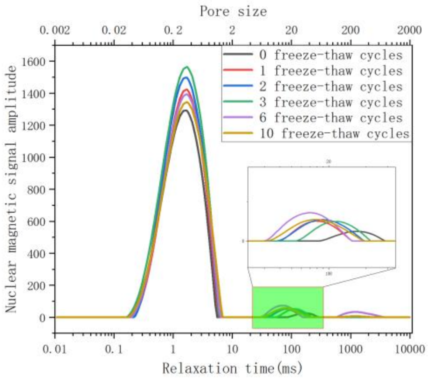

Fig.1 Nuclear Magnetic Resonance results

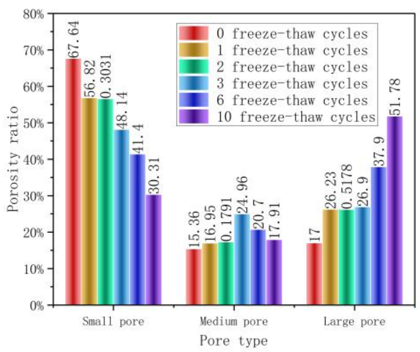

Fig.2 Different freeze-thaw cycle number T_2 spectrum

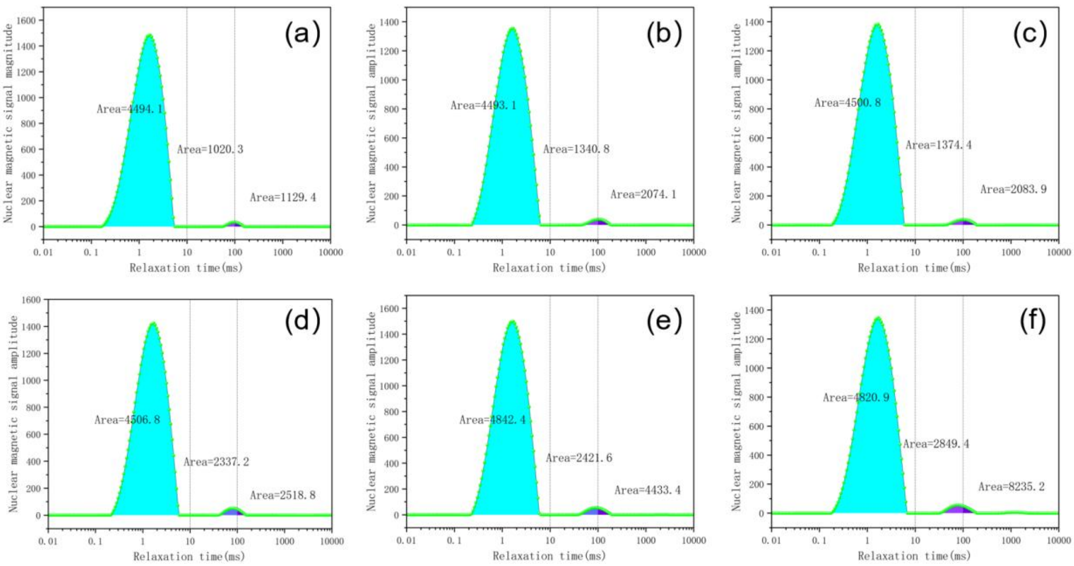

Fig.3(a-f) Variations in the surface area of NMR spectra of samples subjected to different freeze-thaw cycle numbers.

During freezing, water infiltrates clay pellets due to gravity and diffusion, leading to pore and crack formation. The development of these pores and cracks weakens interlocking forces, decreasing internal friction. Water attached to large stones separates soil, weakening bonding forces and decreasing cohesion in the soil-rock mixture.

2.3 Fractal characteristics of pore structure

Fractal dimension reflects effective occupation value of complex body in space, scientific measure of complexity of object's structure. It does not characterize size of pores, but complexity and spatial distribution characteristics. Larger fractal dimension indicates higher non-uniformity and complexity, uneven spatial distribution, more branching leading to rough pore throats, ultimately resulting in deterioration of physical properties. Based on NMR detection principle and relationship between pore cumulative volume, pore volume fraction, fractal dimension, and relaxation time, can be inferred that[11]:

$$\lg S_v = (D-3)\ \lg T_{2,\ max} + (3-D)\ \lg T_2 \tag{1}$$

Where: S_v is the pore volume fraction; T_2 is the relaxation time, in milliseconds; D is the fractal dimension of the pores.Using T_2=10ms as the threshold, the $\lg S_v$-$\lg T_2$ curve of medium-large and small pores is linearly segmented. The slope represents fractal dimensions D_1 and D_2. Results in Table 1 show D_1 initially increasing, then slightly decreasing before steadily rising. Structure complexity increases with more freeze-thaw cycles, leading to irregular stress paths and crack shapes.Post-first cycle, moisture distribution evens out, making pore structure more uniform. Some small cracks compact, slightly reducing fractal dimension. D_2, representing medium-large pores, fluctuates upward, influenced by various factors. Freeze-thaw cycles can split large pores into small ones, increasing overall structural complexity and decreasing soil particle aggregation, lowering internal friction and cohesion in the samples.

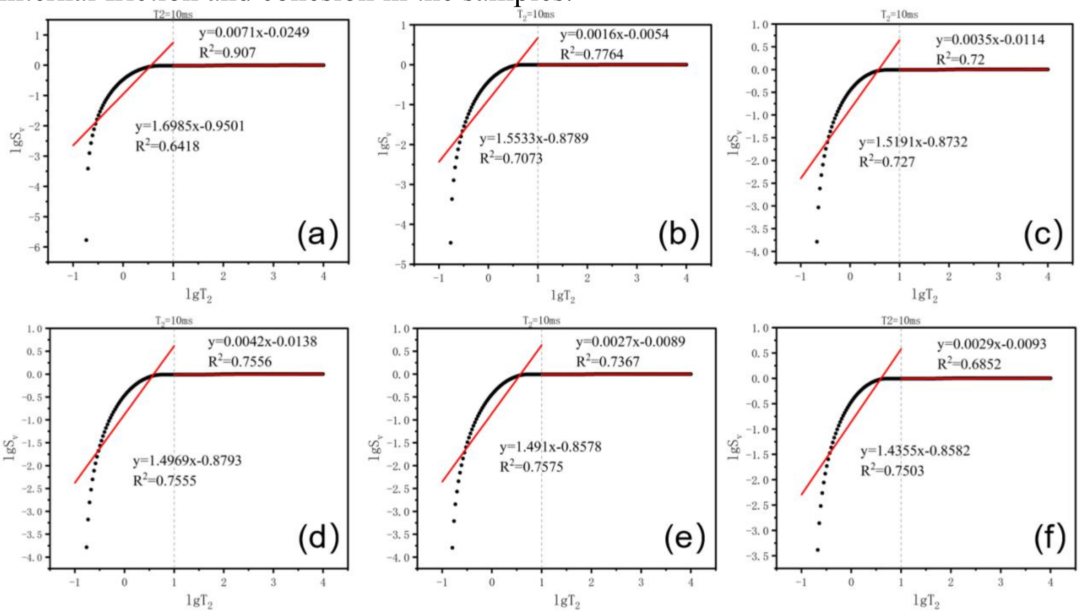

Fig.4(a-f)Piecewise fitting of fractal dimension versus the number of freeze-thaw cycles

Table1. Nuclear magnetic resonance fractal dimension

The number of freeze-thaw cycles	0	1	2	3	6	10
D_1	1.301	1.480	1.446	1.503	1.509	1.564
D_2	2.992	2.996	2.998	2.995	2.997	2.997

3. Triaxial shear test

Conduct CU triaxial shear tests on specimens subjected to a specified number of freeze-thaw cycles. Apply confining pressures of 100, 150, and 200 kPa, and control the shear rate to rise at 0.08 mm/min until axial strain reaches 20% failure criterion. Fig.5 shows stress-strain curves under different freeze-thaw cycles. Use Mohr-Coulomb theory to calculate shear strength parameters after obtaining test results under the three confining pressures.

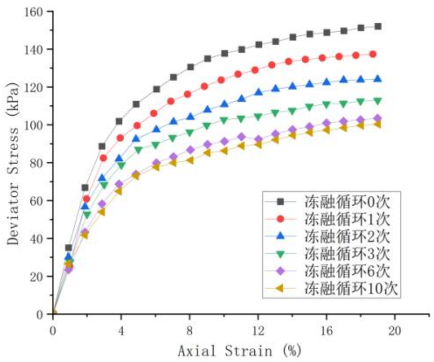

Fig.5 Stress-strain curve

Fig6 Failure morphology

Under different freeze-thaw cycles, the shear strength parameters of the sample are shown in Table 2, with the cohesion decreasing significantly as freeze-thaw cycles increase. The weakening of the original cohesion between soil particles occurs continuously as freeze-thaw and migration forces change during different cycles.

Table2 .The shear strength parameters

The number of freeze-thaw cycles	0	1	2	3	6	10
Cohesion(c/kPa)	127.6	126.3	121.4	116.6	108.7	101.2
Internal friction angle(φ/°)	43.5	42.6	42.9	42.4	40.8	40.6

The internal friction angle decreases from 43.5° to 40.6° after ten cycles, showing a fluctuating decreasing trend. Water infiltration into aggregates, freezing, and expansion cause sheet-like particles to crush, reducing interparticle contact force and leading to a continuous decrease in the internal friction angle. Shear dilatation in the failure mode of Figure 6 increases contact area and force between particles, enhancing the internal friction angle. Under confining pressure, the sample's structure becomes more compact, explaining the slight increase in internal friction angle after the second cycle. After multiple cycles, particle positions stabilize, and with proper water content control, the internal friction angle tends to stabilize after an initial decrease.

4. Conclusion

The trend of strength parameters of cohesive soil-aggregate mixtures obtained through investigation of microscopic structure and morphological changes shows that they vary as the number of freeze-thaw cycles increases.

(1)The characteristic of fractal dimension D_1 showing an initial increase followed by a slight decrease and then a continuous increase infers that the number of cracks and voids within the material's internal pore structure increases, leading to a continuous rise in overall material heterogeneity and irregularity. This, in turn, causes the shear strength parameters to first decrease, then slightly rebound, and finally decrease again.

(2)The expansion of the T_2 peak indicates an increase in both the size and quantity of pores, leading to a decrease in internal bonding strength, resulting in a steady decline in cohesion force measured in triaxial experiments.

(3)The phenomena of shear dilation and the fluctuation of fractal dimension D_2 of medium-to-large pores both indicate that freeze-thaw action can optimize the contact performance between particles, resulting in a fluctuation pattern of the internal friction angle, which reduces the process to be small and slow.

(4)Freeze-thaw action causes a small amount of water to precipitate, reducing the amount of water inside the sample, thereby decreasing the risk of structural instability and promoting the stability of shear parameters and strength.

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